

Searching for Radio Pulsars in Fermi LAT Sources

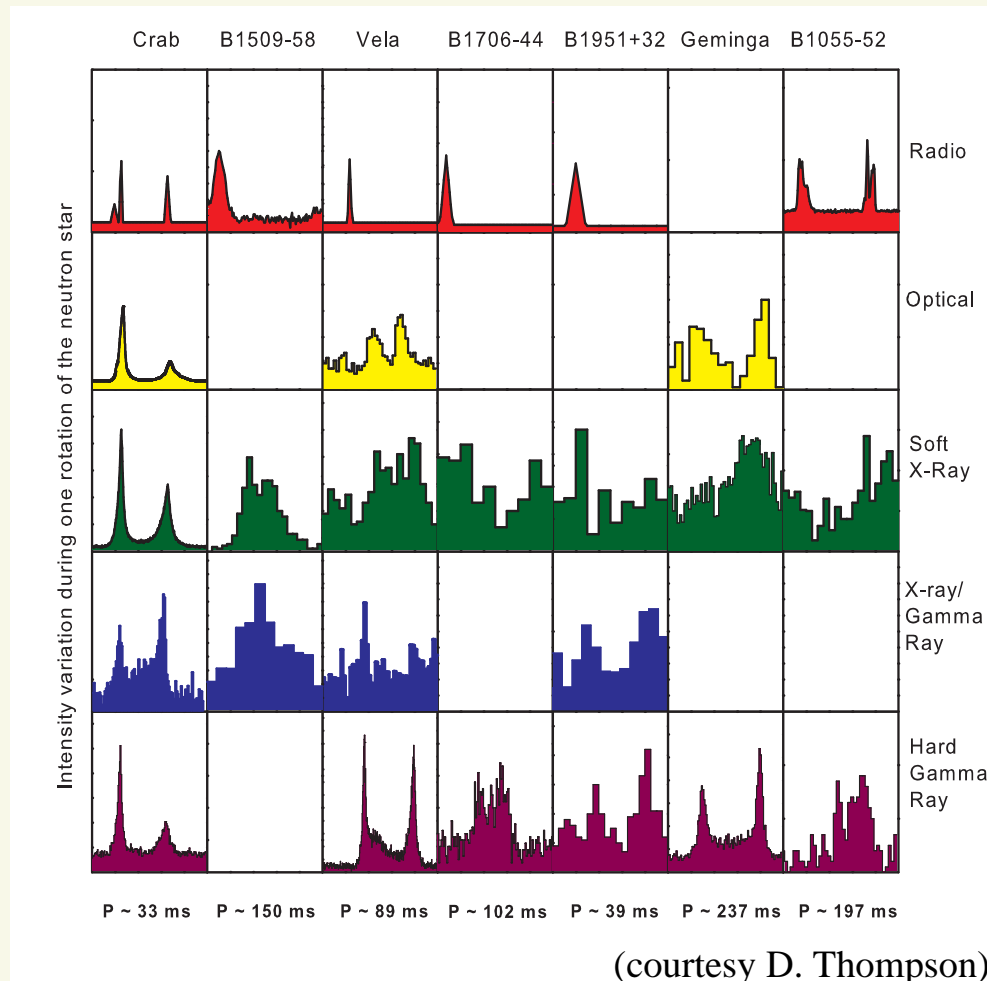
Fernando Camilo*
Columbia University

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*On behalf of the Pulsar Search Consortium and LAT colleagues

Gamma-ray pulsars in the EGRET era

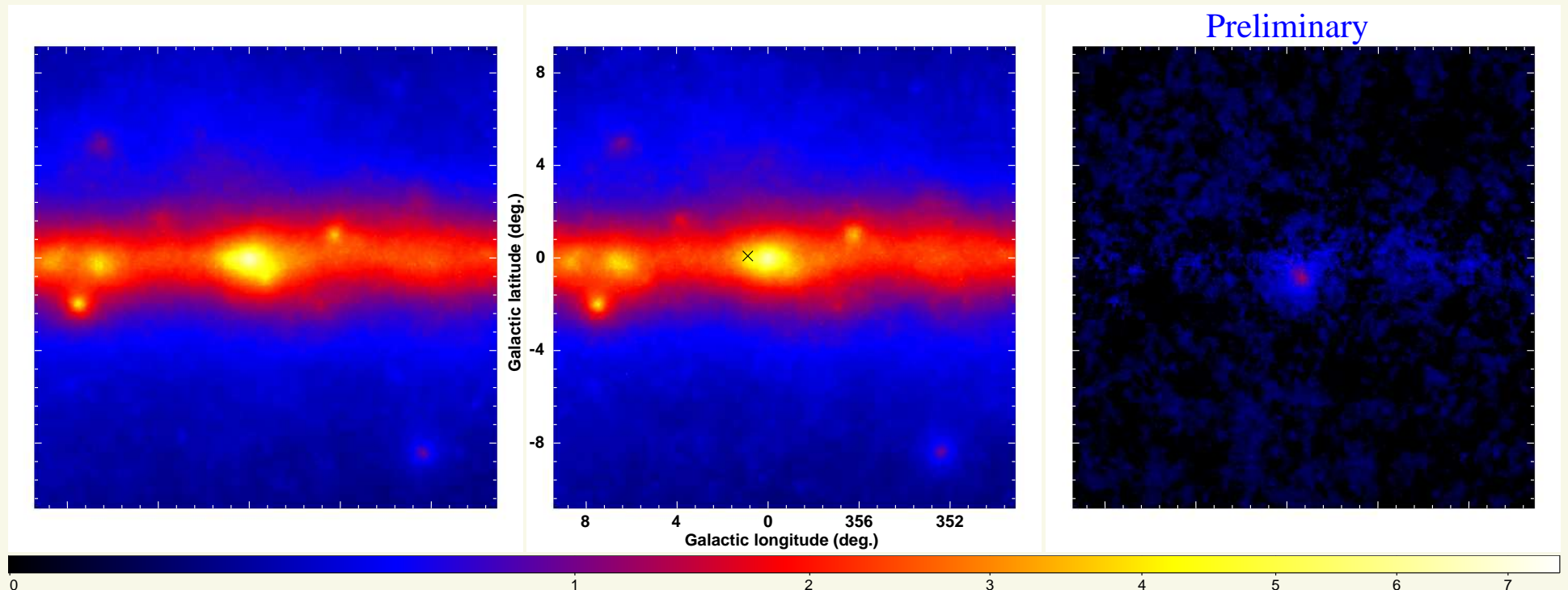
During the *Compton Gamma-Ray Observatory* era, only 6 pulsars were known to emit > 100 MeV pulsations:



- Detected via photon folding with radio/X-ray ephemerides
- Mainly high spin-down luminosity ($\dot{E} = -I\omega\dot{\omega}$), relatively nearby

Fermi-LAT and its many sources

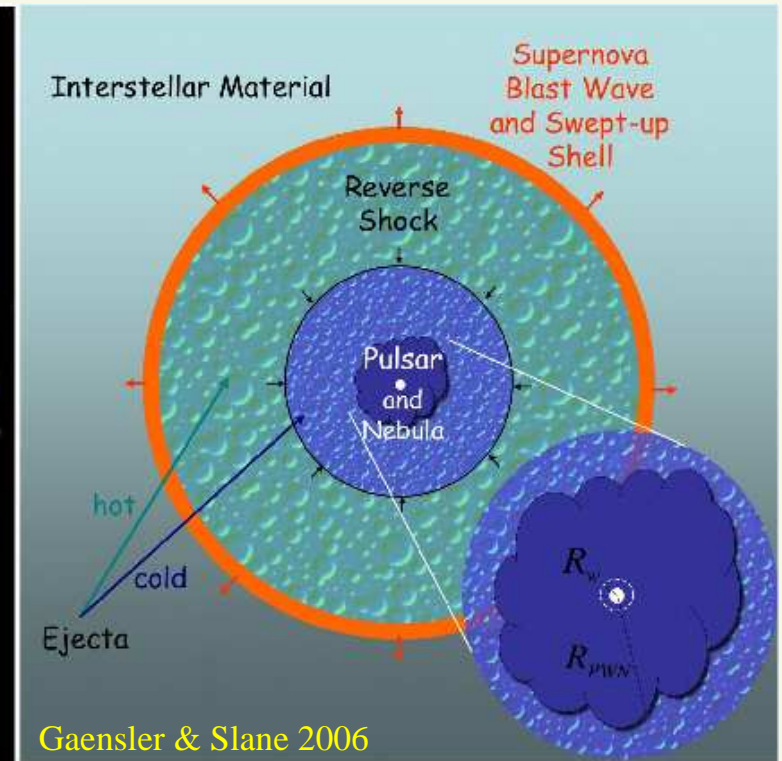
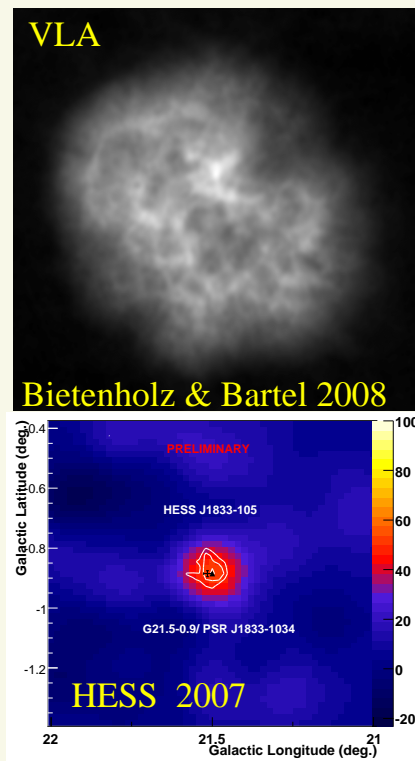
Identifying pulsars in LAT sources is important for pulsar science (e.g., emission mechanisms), but also for other population and background studies:



The “Mouse” pulsar (J1747–2958) after 1.5 years

How do we go about identifying promising (energetic) pulsars and detecting pulsations?

Rotation-powered pulsars and their wind nebulae



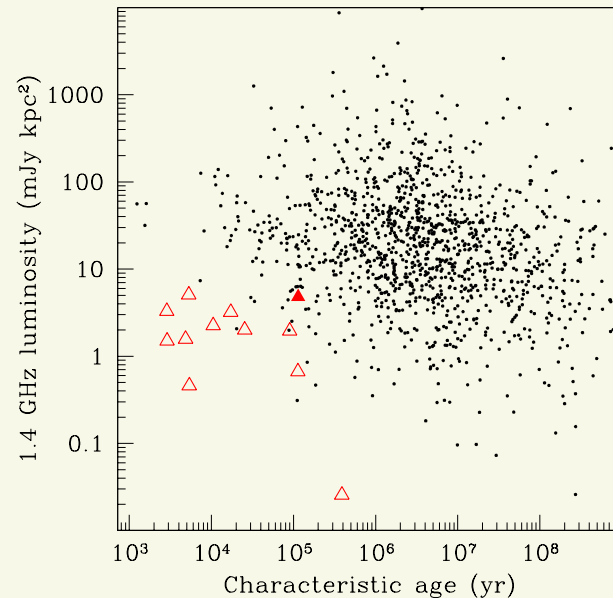
SNR G21.5–0.9 ($\tau \approx 1$ kyr); $P = 61$ ms, $\dot{E} = 3 \times 10^{37}$ erg s $^{-1}$ (Gupta et al. 2005; Camilo et al. 2006)

Central nebula powered entirely by confined relativistic magnetized particle wind. Such PWNe (~ 50 known) are important for the study of their environments, and of relativistic flows, particle acceleration mechanisms, etc. They also point unmistakably to pulsars.

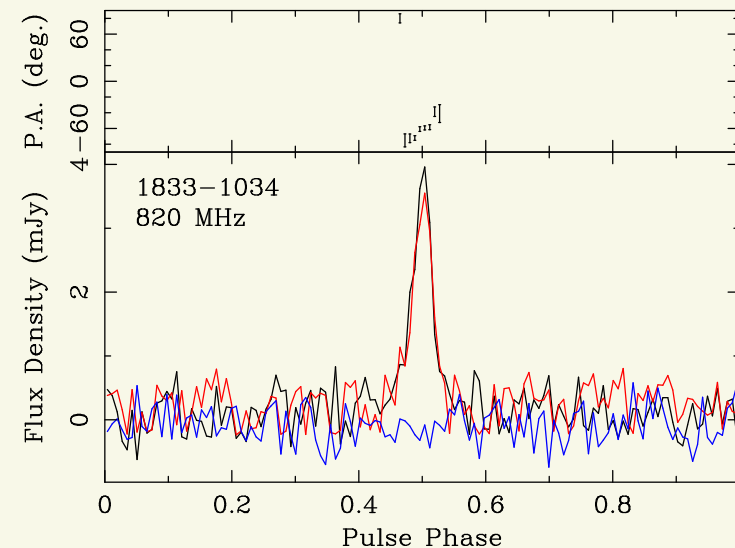
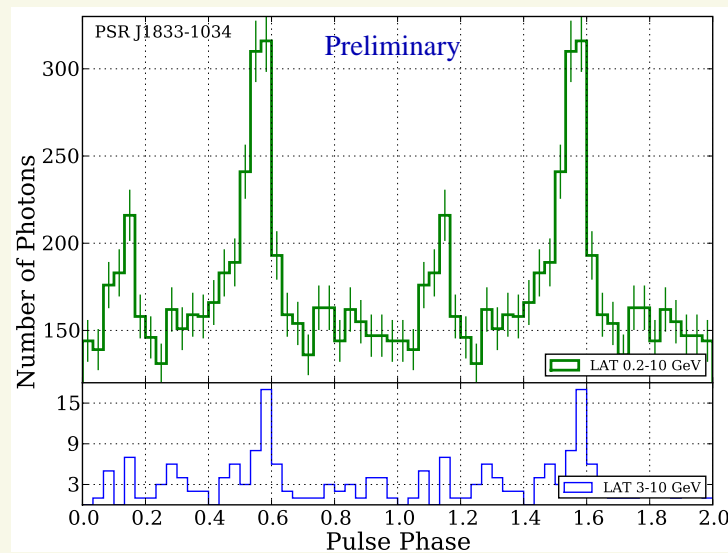
Discovery of pulsations leads to \dot{E} , estimate of distance. To understand the central engine, we also need to address pulsed emission — in γ -rays: while $L_\gamma \ll 10^{-3} \dot{E}$, $L_\gamma \sim \dot{E}$.

From deep radio searches of PWNe to LAT pulsations

Over the past decade, deep directed searches and discoveries (implications for radio beaming fraction and luminosity distribution):

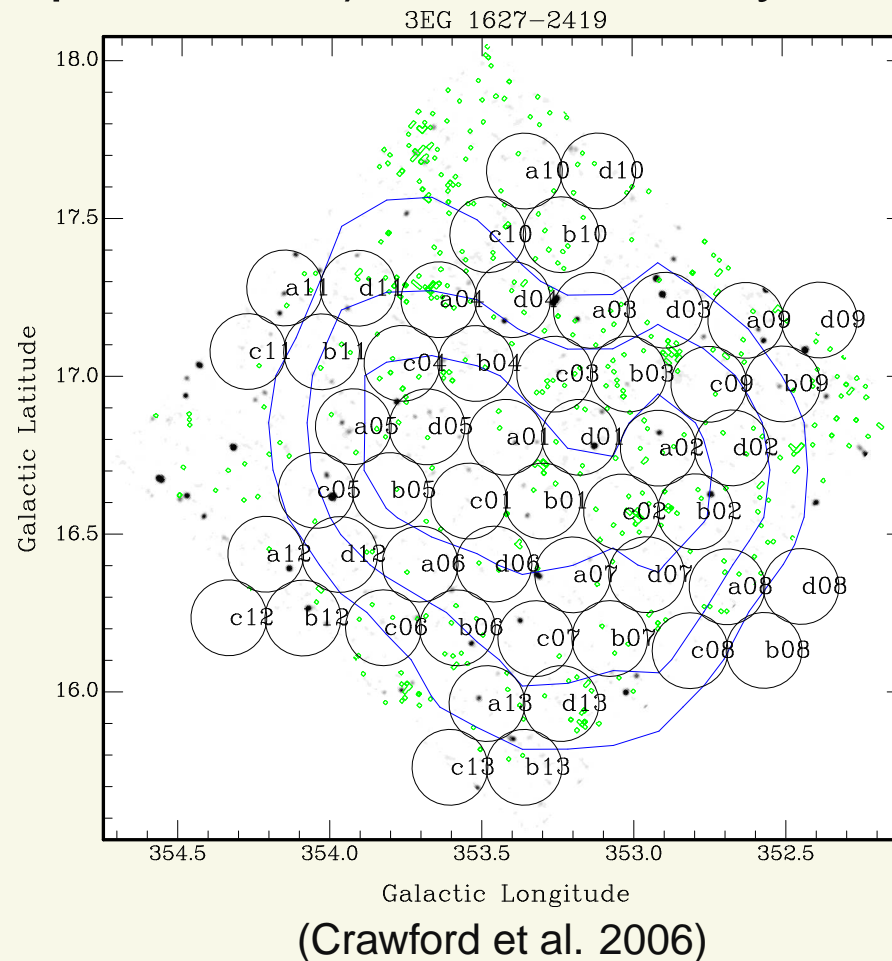


LAT photon folding on radio ephemeris leads to γ -ray pulsations:



Searching unidentified gamma-ray sources

Very tough (and unproductive) in EGRET days:

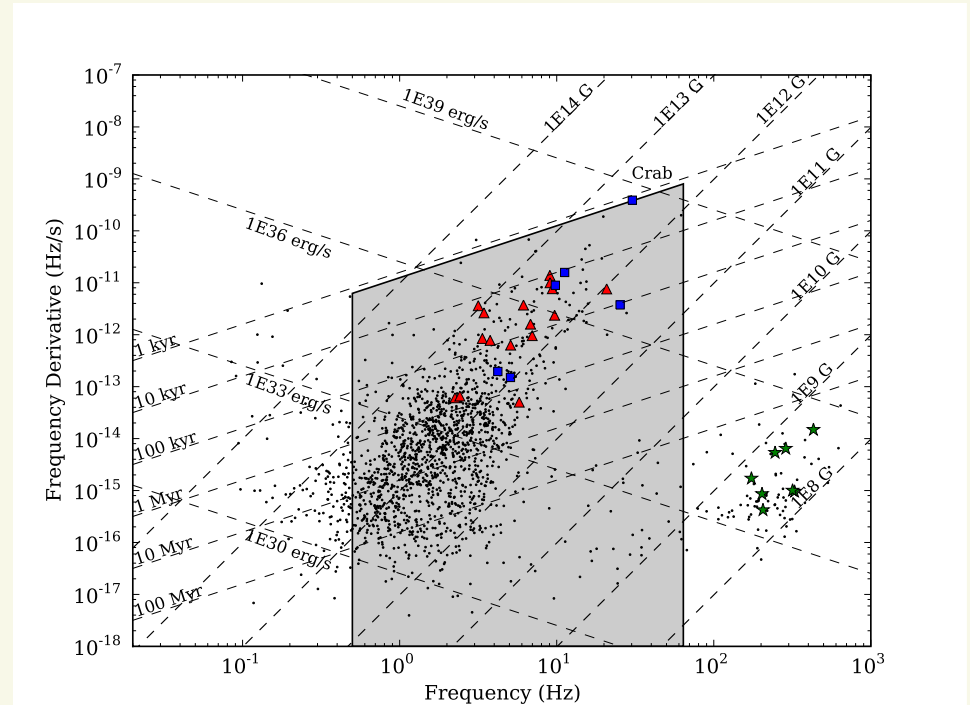
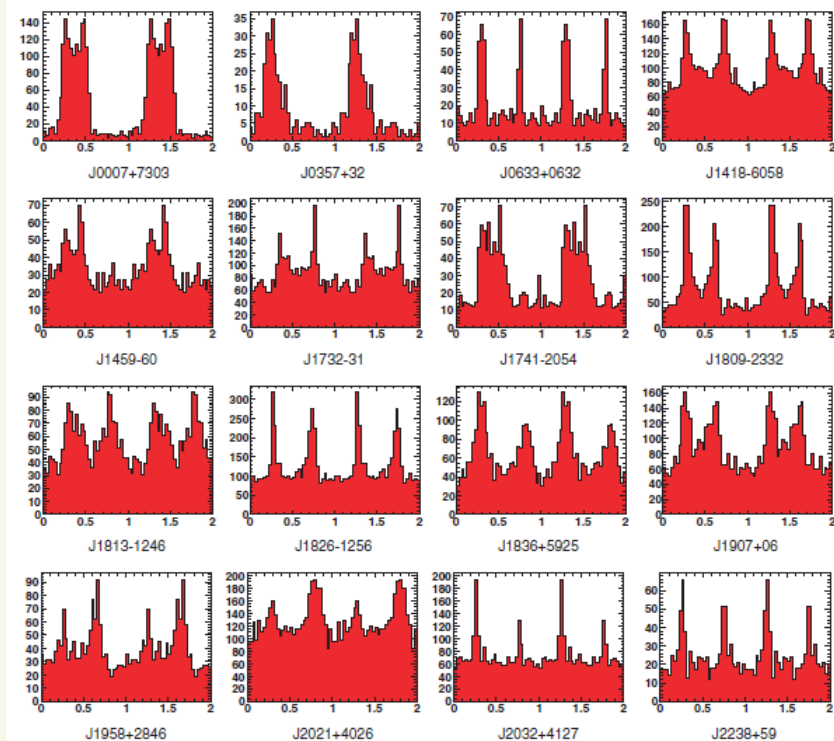


Easier to do with smaller LAT error boxes: $r_{95} \sim 0.1^\circ$ often well-matched to radio telescope beam HWHM $\sim 3'-15'$.
We'll come back to this...

Wonderful LAT surprises: blind search pulsars

24 pulsars found in blind frequency searches of γ -ray photons!

(Abdo et al. 2009; Saz-Parkinson et al. 2010)



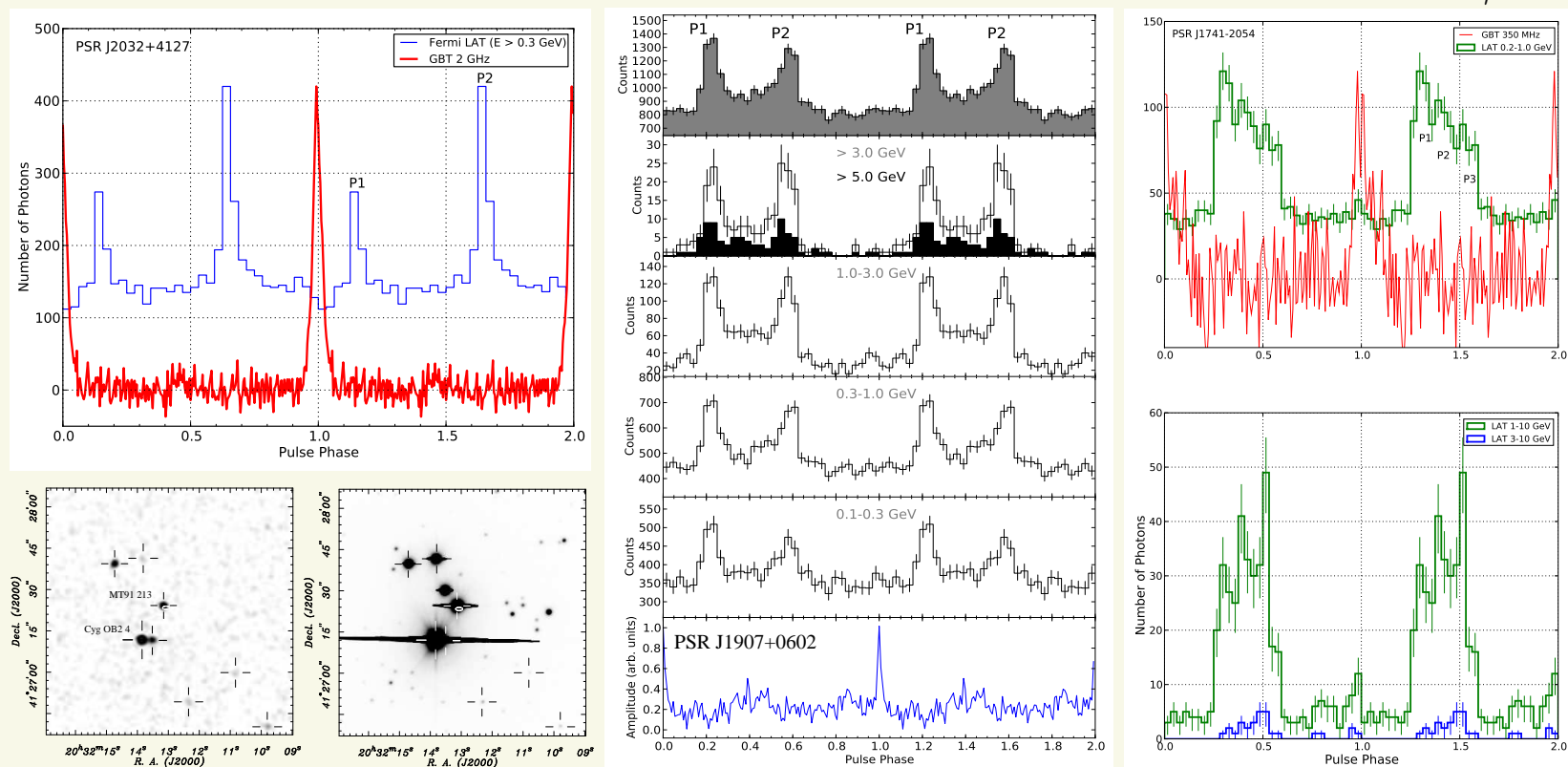
Rotational properties comparable to EGRET pulsars

Some of these are located in SNRs/PWNe that had been searched deeply in radio before, but most hadn't. Are they also radio pulsars? Let's find out...

Radio searches of LAT “blind search pulsars”

After very deep searches at GBT, Parkes, Arecibo, only 3 of 25 γ -ray-selected pulsars have been detected in radio (*beaming*):

- Radio: δ ; dispersion measure \Rightarrow distance estimate $\Rightarrow L_\gamma$

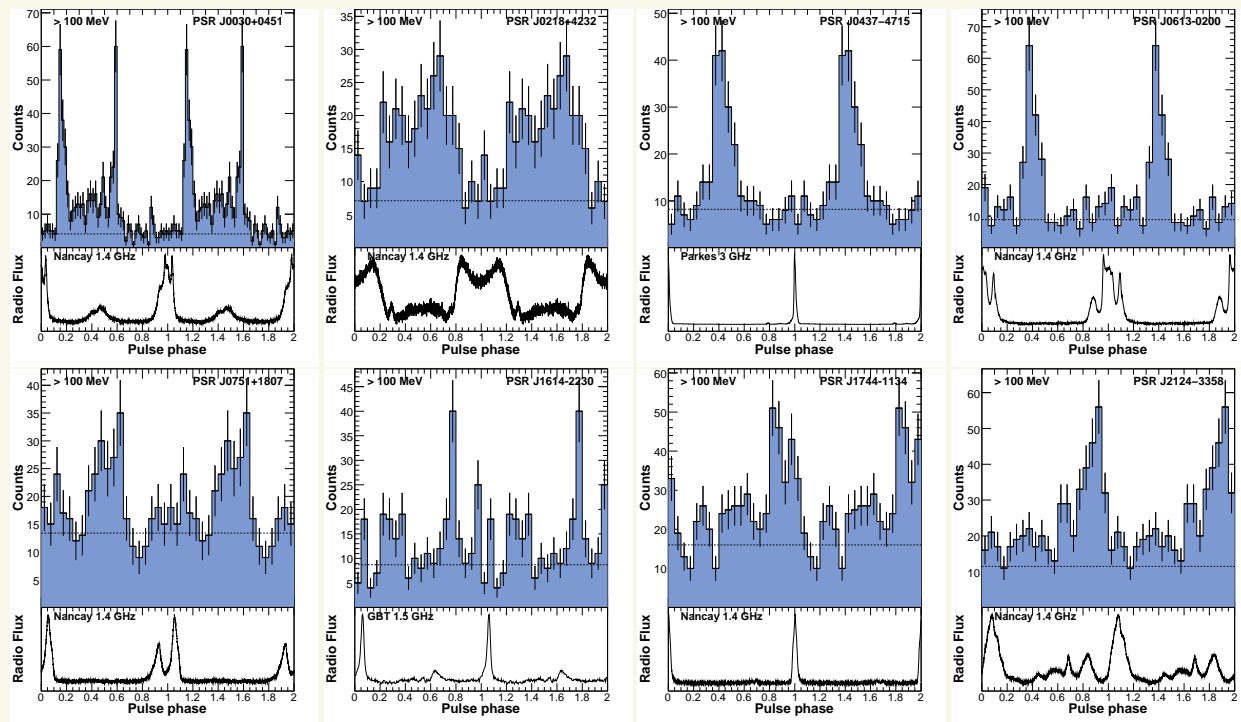


(Camilo et al. 2009; Abdo et al. 2010)

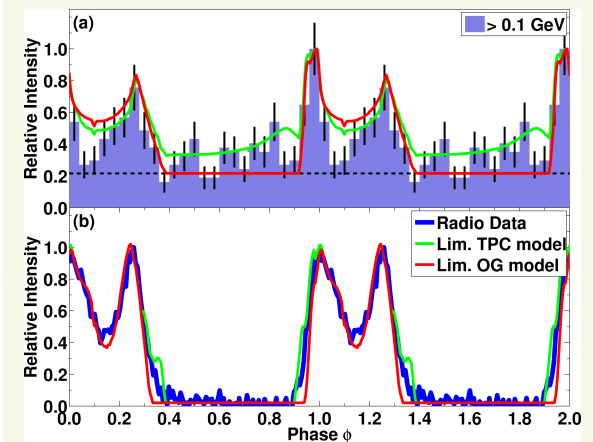
- Two likely account for TeV sources
- J1741–2054 at ~ 400 pc, $\dot{E} = 10^{34}$ erg s $^{-1}$, $\tau_c = 0.4$ Myr (\sim Geminga; 5 others among 24, but unknown distances)
- Two have smallest radio luminosities among known pulsars

A new population: LAT pulsations from known MSPs

LAT pulsations have been detected from 9 mainly nearby MSPs ($d < 1$ kpc) using radio-derived ephemerides:



(Abdo et al. 2009)



J0034-0534: co-located radio and γ -rays (Abdo et al. 2010)

MSP pulsations cannot be discovered in blind searches of γ -ray data. But many LAT sources remain unidentified. Some may be MSPs, especially at high Galactic latitudes...

LAT pulsations in radio-selected young pulsars, & state of play

Progress in this class, the main one known prior to *Fermi*, has been harder to make: > 200 radio pulsars with $\dot{E} > 10^{34} \text{ erg s}^{-1}$ timed on a regular basis; only about 20 with detected LAT pulsations.

As of September 2009, about 60 γ -ray pulsars known ($10\times$ EGRET): 80% of non-MSPs have large \dot{E} ($> 10^{35} \text{ erg s}^{-1}$), while remaining 10 are older ($\tau_c = P/2\dot{P} \sim 0.1\text{--}1 \text{ Myr}$) and with lower \dot{E} (see 1st LAT pulsar catalog; Abdo et al. 2010):

- Pulsars with LAT pulsations are \sim nearby, with high spin-down flux
- Spectra of the form $dN/dE \propto E^{-\Gamma} \exp(-E/E_c)$ ($\Gamma \sim 1.5$, $E_c \sim 2 \text{ GeV}$)
- For the most part, outer magnetospheric (not polar cap) emission
- $\eta = L_\gamma/\dot{E}$; $L_\gamma = 4\pi f_\Omega d^2 F_\gamma$
 $\eta(\dot{E})$ still eludes us (poorly determined d and f_Ω)
- Profile modeling and phase-resolved spectroscopy $\Rightarrow f_\Omega$ (Harding, DeCesar, Johnson, Venter; Romani, Watters; Spitkovsky, & co. at it)
- Much modeling/population synthesis remains to be done

Work continues in γ -ray blind-search and photon-folding areas.

What about radio searches of unidentified LAT sources?

LAT catalogs, and PSC

Fermi-LAT catalogs:

- Bright Source List (based on 3 months of data, available early 2009): 205 sources ($> 10 \sigma$), 50 unidentified
- 1FGL (based on 11 months of data, available early 2010): 1451 sources ($\gtrsim 4 \sigma$, but 161 mainly at $|l| < 60^\circ$, $|b| < 1^\circ$ have uncertain properties or existence), 630 unidentified

Fermi Pulsar Search Consortium: aims to efficiently organize collaborative radio and γ -ray work to search “blind search pulsars” and unidentified LAT sources.

Participating telescopes: GBT, Parkes, Nançay, Effelsberg, Arecibo.

GBT BSL searches

Selected 30 BSL sources that are non-variable and not associated (e.g., with possible PWNe/SNRs).

Searched 25 visible from GBT (PI Ransom; others searched at Parkes, Nançay, Arecibo) at 820 MHz ($B = 200$ MHz, $T = 45$ min).

With “acceleration searches”, discovered **3 MSPs** and detected 1 more in 8 sources at $|b| > 5^\circ$! (And discovered 1 unassociated slow pulsar at low $|b|$.)

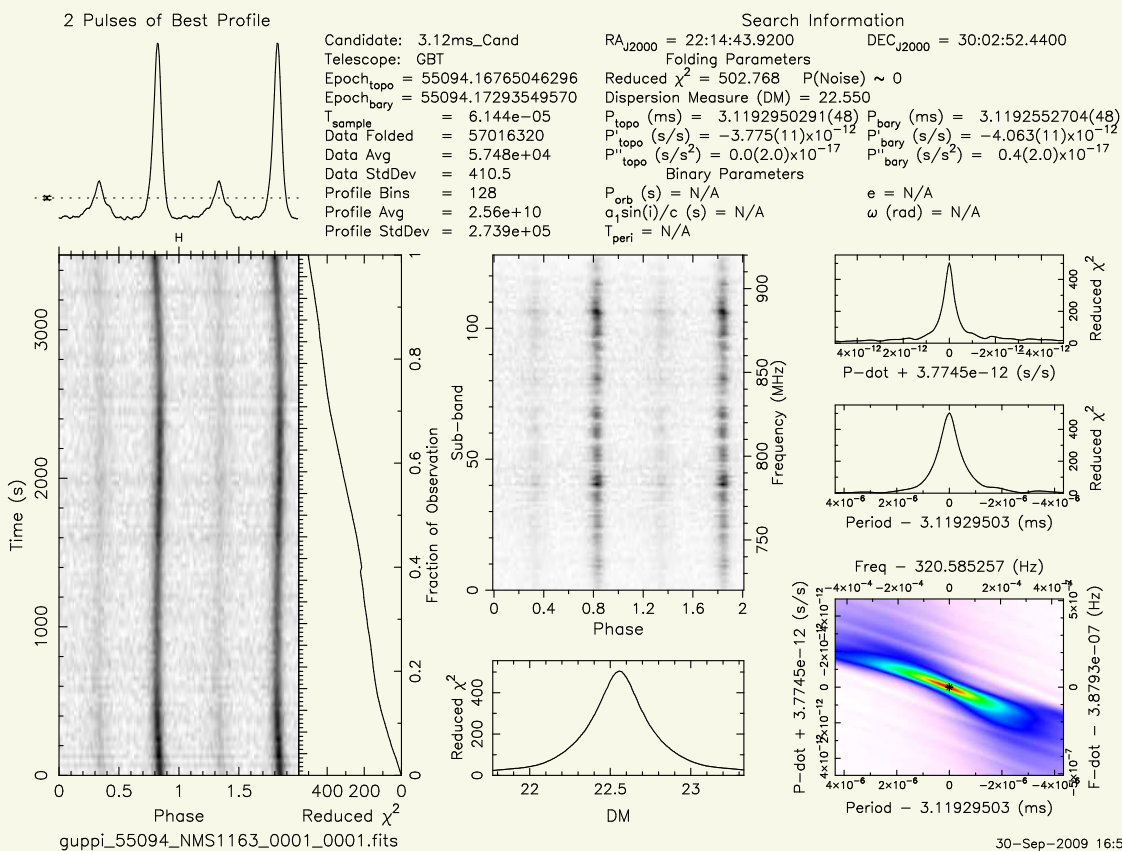
0FGL J2214.8+3002:

$P = 3.1$ ms

$P_b = 10$ hr

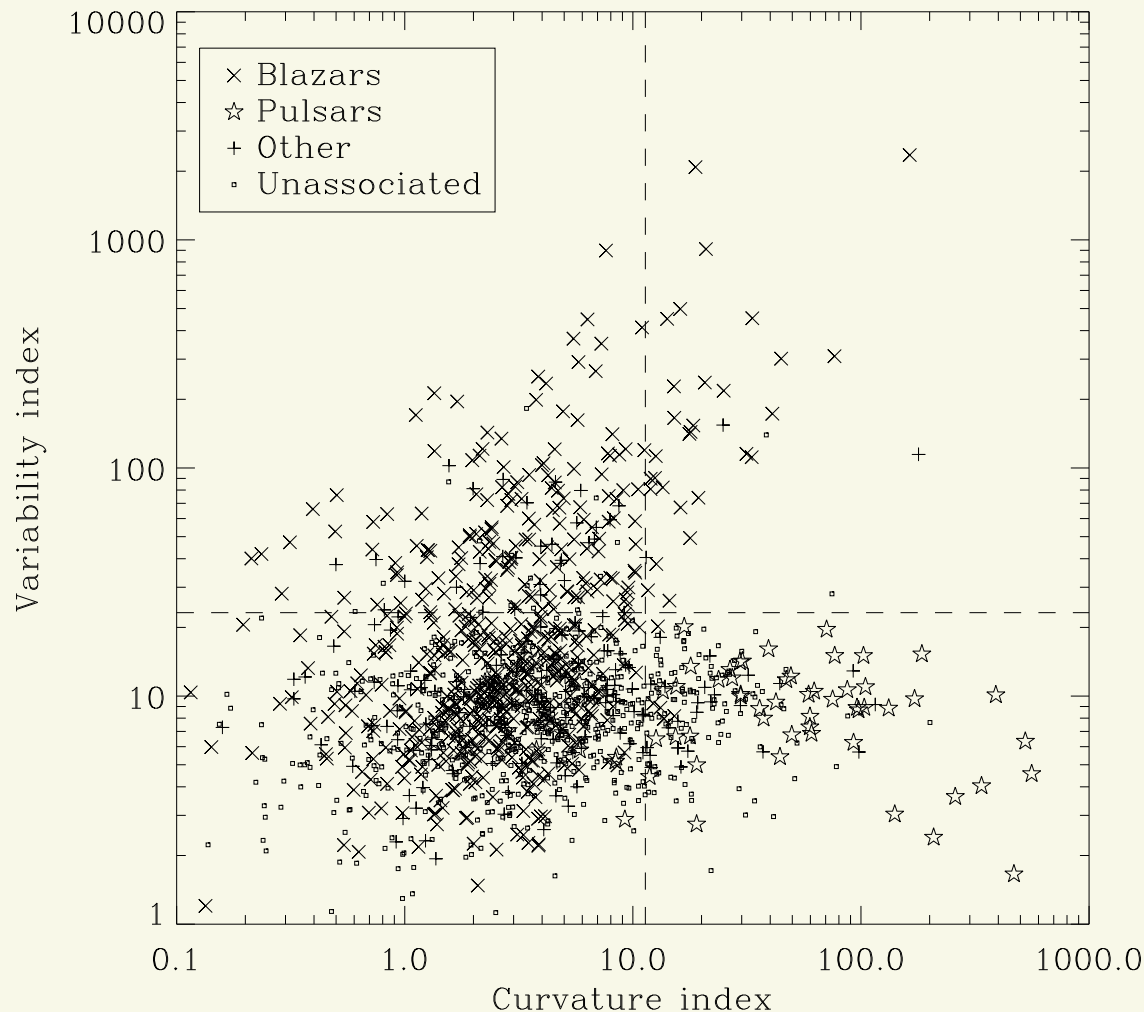
$m_c > 0.01 M_\odot$

$d \sim 1.5$ kpc



Wading through the unidentified sources...

With much larger unidentified sample, need to prioritize targets.
Basic idea is to identify non-variable sources with “pulsar-like” spectra:



(Abdo et al. 2010 [1FGL Cat])

Ranking unidentified LAT sources for “pulsariness”

Matthew Kerr and Elizabeth Ferrara have implemented this in different ways:

- MK: generated finely-binned SEDs and obtained spectral parameters from a PL+EC fit to 14 months of data. Then obtain qualitative 3-bin ranking based on staring at SED, strength of cutoff, variability, and association information.
- EF: use “curvature index” (deviation of 5-bin SED from PL), spectral index, and variability, from 1FGL catalog. Use known pulsar population to help determine threshold values for each of these quantities to define “pulsar-like” regions, and derive a quantitative ranking for each source automatically.

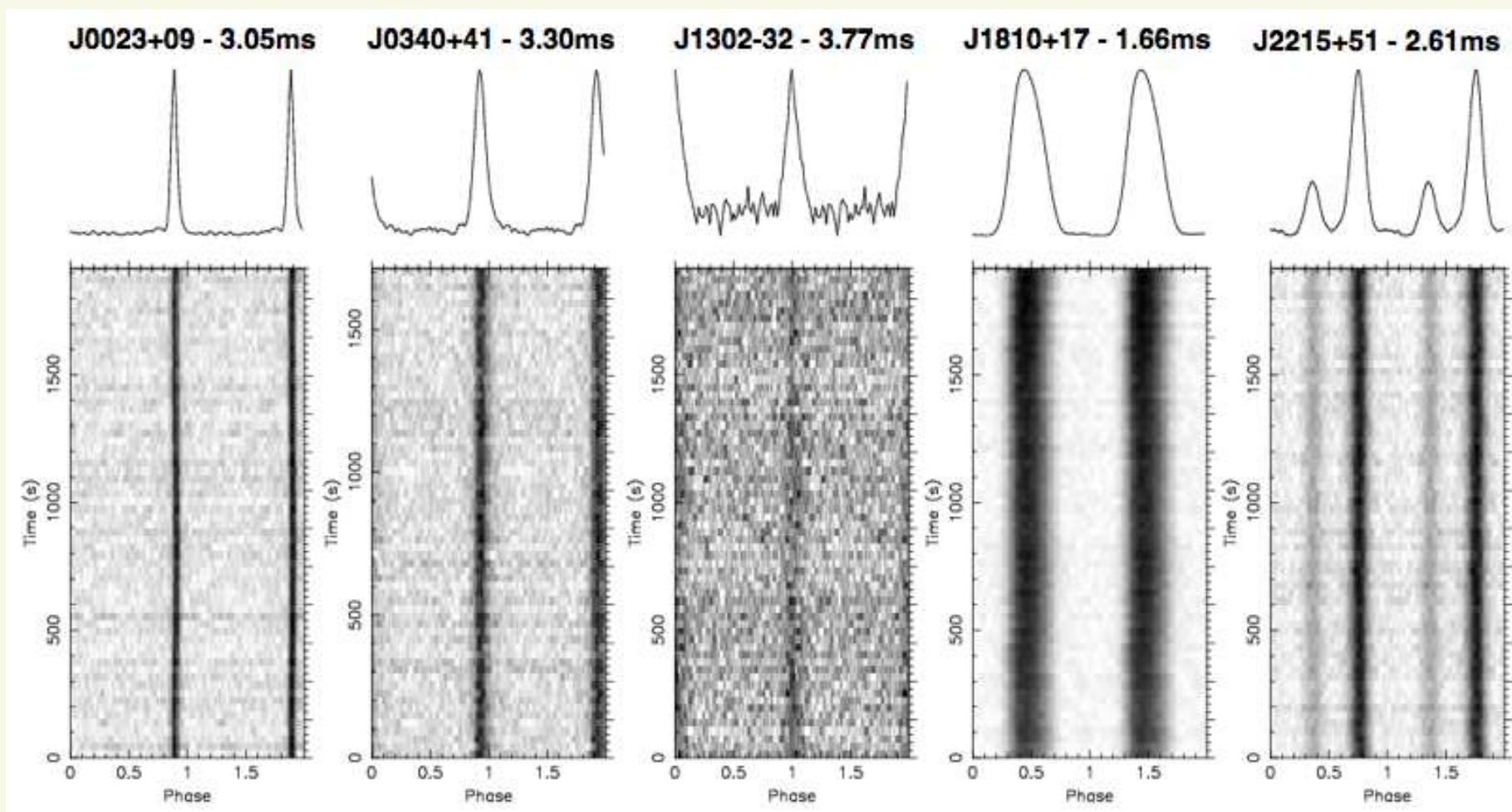
Significant but not overwhelming overlap in both rankings.

MK method appears preferable in some respects (e.g., EF suffers from more AGN contamination), but it’s good to have both.

Searches galore: non-BSL at GBT

GBT (PI Roberts): searched 47 1FGL $|b| > 5^\circ$ sources at 350 MHz ($B = 100$ MHz, $T = 32$ min).

While analyzing 215 s chunks (1/9) of data, found **5 MSPs** (of which 3 are eclipsing/“black widow” systems)!

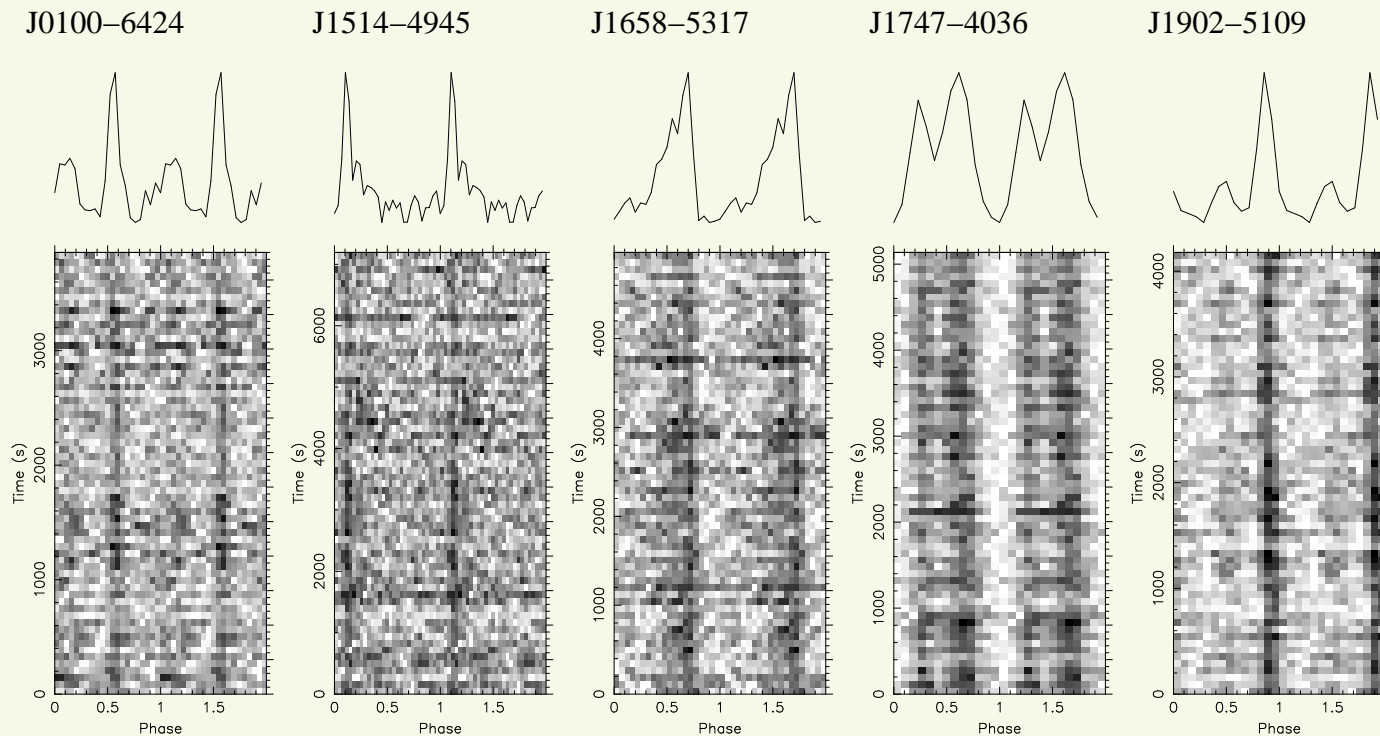


More searches: Nançay, Effelsberg, Arecibo, Parkes...

- **Nançay** (PI Cognard): 20 sources (BSL and 1FGL) searched at 1.4 GHz ($B = 128$ MHz, $T = 1$ hr), **2 MSPs** discovered.
- **Effelsberg** (PI Kramer): 288 sources (193 at $|b| > 5^\circ$) searched at 1.4 GHz ($B = 300$ MHz, $T = 10$ – 32 min), **1 MSP** discovered (so far only 153 analyzed, and RFI is significant).
Work in progress...
- **Arecibo** (PI Freire): 5 BSL sources searched at 327 MHz ($B = 50$ MHz, $T = 30$ min), of which 2 are MSPs discovered first at GBT/Nançay, and 2 others became LAT blind search pulsars. New 327 MHz search of 45 1FGL sources underway...
- **Parkes** (PI Keith): 12 sources (4 at $|b| > 5^\circ$; BSL and 1FGL) searched at 1.4 GHz ($B = 340$ MHz, $T = 4.8$ hr), **2 MSPs** and 1 slow (unassociated) pulsar discovered, 1 MSP detected. Another 7 1FGL sources ($T = 0.5$ – 1 hr) searched.

And some more Parkes searches

Parkes (PI Camilo): 15 sources (2 BSL + 13 1FGL, all at $|b| > 5^\circ$)
searched at 1.4 GHz ($B = 288$ MHz, $T = 1$ – 2 hr):
5 MSPs discovered, 1 MSP detected (in 2 weeks).

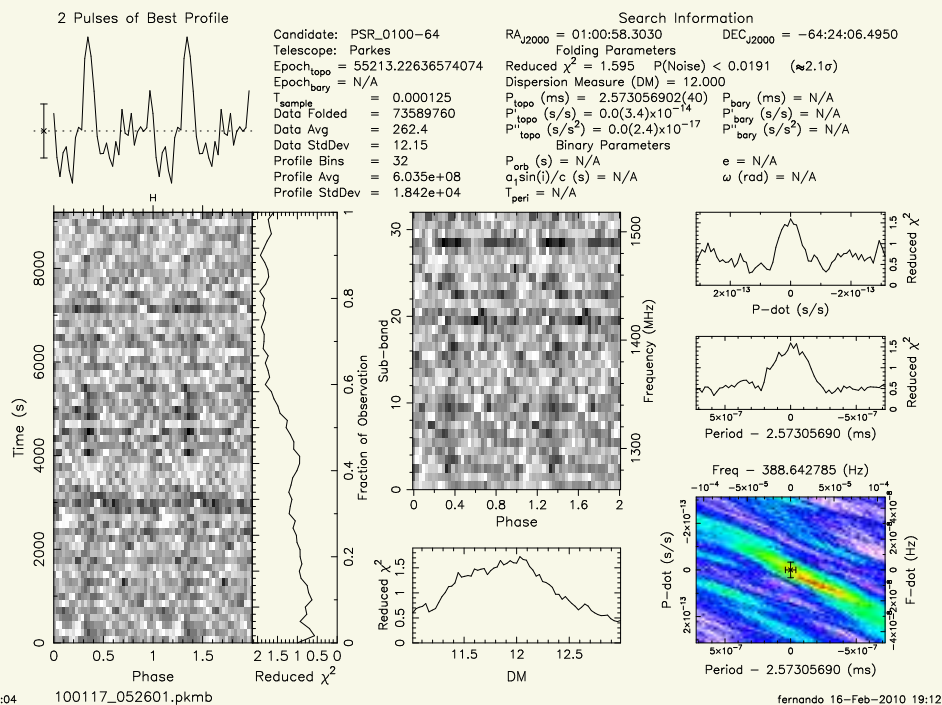
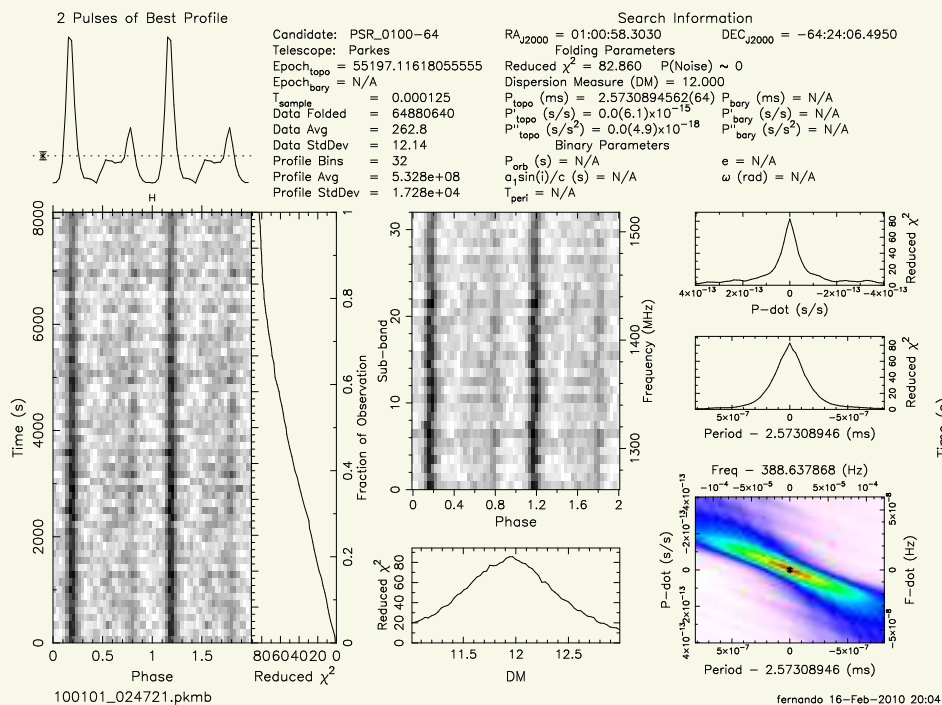


$P=2.57\text{ms}$, $\text{DM}=12$ $P=3.58\text{ms}$, $\text{DM}=31$ $P=2.43\text{ms}$, $\text{DM}=31$ $P=1.64\text{ms}$, $\text{DM}=153$ $P=1.74\text{ms}$, $\text{DM}=36$

Fantastic success rate (cf. ~ 60 field MSPs in 28 years); these
directed searches up to $> 10\times$ more sensitive than previous ones.
But could some of the other 9 sources still harbor MSPs?

Finding LAT MSPs through interstellar weather

PSR J0101–6422: received flux varies by a factor of over 50 due to scintillation in ISM! On some days the pulsar is not detected.

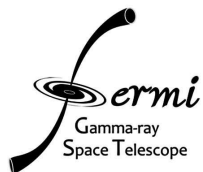
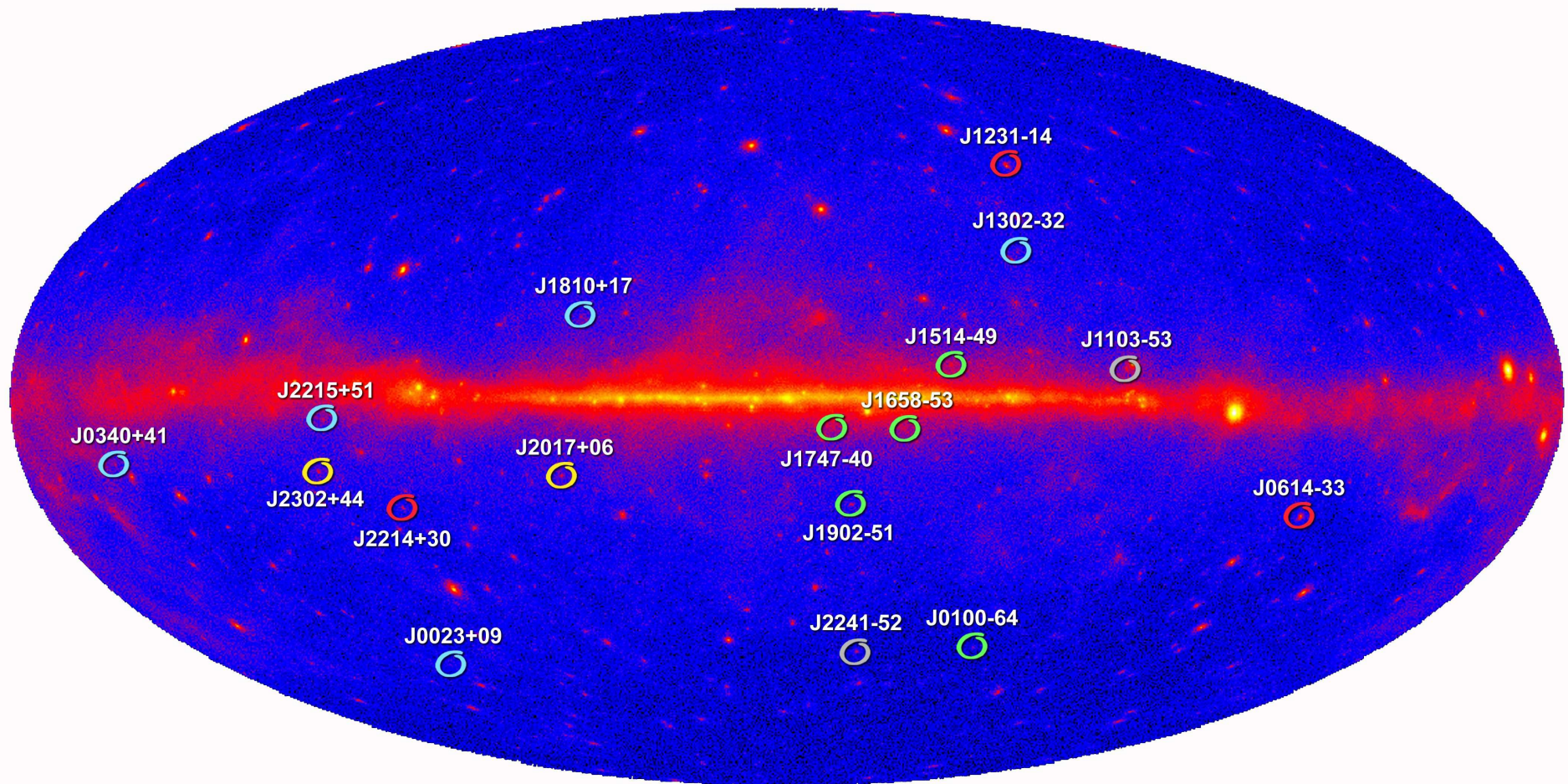







PSR J1514–49, also discovered at Parkes (in a BSL source), is detected on less than half the observations!

Implication for searching: must search “good” sources several times, also because of eclipses (*how many times?*)

MSPs in unidentified LAT sources

New Millisecond Radio Pulsars Found in Fermi LAT Unidentified Sources



-  Led by Fernando Camilo (Columbia Univ.) using Australia's CSIRO Parkes Observatory
-  Led by Mallory Roberts (Eureka Scientific/GMU/NRL) using the NRAO's Green Bank Telescope
-  Led by Scott Ransom (NRAO) using the Green Bank Telescope
-  Led by Ismael Cognard (CNRS) using France's Nançay Radio Telescope
-  Led by Mike Keith (ATNF) using Parkes Observatory

MSPs in unidentified LAT sources: some interim thoughts

- We cannot yet determine what fraction of unidentified high- $|b|$ sources contain radio MSPs: repeated searches (and proper analysis) required — and *we must somehow determine what are bona fide “pulsar-like” sources!*
- Are MSPs important for high- $|b|$ γ -ray background (e.g., Faucher-Giguère & Loeb 2010, at 10–20%)?
- γ -ray pulsations detected so far from 6 of 18 new MSPs. Eventually all should have them, with large increase in sample available for emission studies. (1FGL TSs span 40–2986!)
- $8 \lesssim \text{DM} \lesssim 153 \text{ pc cm}^{-3}$ ($0.4 \lesssim d \lesssim 3.4 \text{ kpc}$)
- $1.6 \lesssim P \lesssim 6.7 \text{ ms}$ (possibly skewed to short P ?)
- $0.14 \lesssim P_b \lesssim 125 \text{ d}$, and 3 isolated MSPs (cf. blind searches)
- Unusual prevalence of black widow/eclipsing systems:
indication of shocks? high \dot{E} ?
- Of 37 BSL unassociated sources, 11 have become pulsars (6 MSPs, 4 blind search, 1 young radio-selected); also, only 2 at high $|b|$ remain unidentified. *How well will we do for 1FGL?*

What about youthful pulsars, along the Galactic plane?

Given the initial bounty of high- $|b|$ MSPs, the Galactic plane has been somewhat overlooked – unfairly!

In 29 unidentified LAT sources at $|b| < 5^\circ$ searched at GBT and Parkes (but 18 of them are 1FGL “c”!), one genuine discovery:

PSR J2030+3641:

$P = 200$ ms

$DM = 246$ pc cm $^{-3}$

$\dot{E} = 3 \times 10^{34}$ erg s $^{-1}$

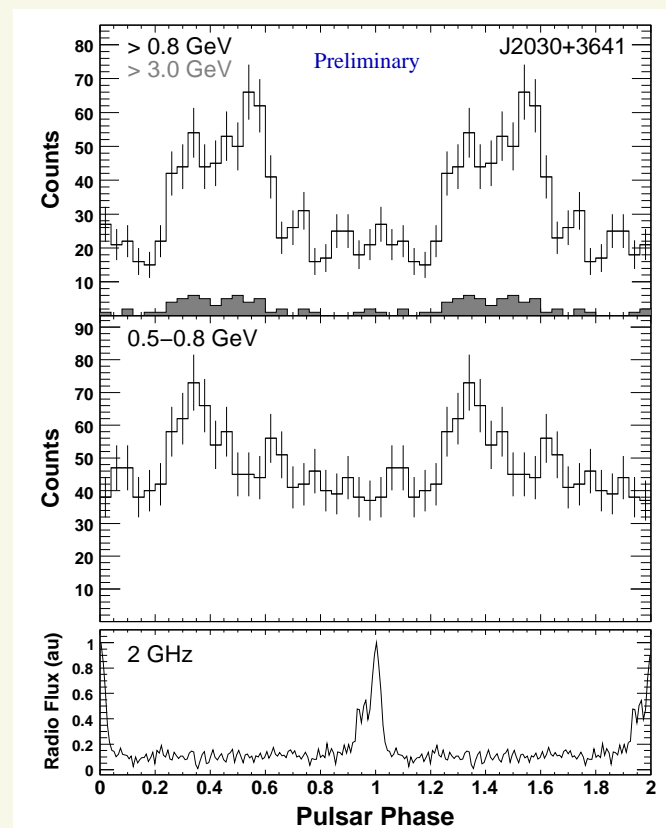
$\tau_c = 0.5$ Myr

Geminga-like pulsar at $\sim 10 \times d$

Most likely very high η

$F_\gamma \sim 1\%$ Geminga’s, hard spectrum
(reason for non-blind discovery?)

How many more of these out there?



We must search every “good” source, no matter its location!